GALACTIC ANTIPROTON AND CPT

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ABSTRACT

Recently, it has been suggested[1] that a significant test of CPT invariance can be derived by comparing the proton lifetime ($\tau_{\mathrm{p}} > 10^{32}$ years) with the antiproton lifetime $\tau_{\overline{\mathrm{p}}}$. CPT invariance would require $\tau_{\mathrm{p}} = \tau_{\overline{\mathrm{p}}}$.

A deviation from CPT induced by gravity effects, if linear in the ratio between proton mass (m_p) to Planck mass (M_{Pl}), could generate a $\tau_{\overline{\mathrm{p}}} \sim 5 \cdot 10^{-31} \cdot \mathrm{M}_{Pl}^2$ (GeV) years $\sim 10^8$ years. A precise measurement of the $\overline{\mathrm{p}}$ galactic flux $\mathrm{N}_{\overline{\mathrm{p}}}$ ($E_{\overline{\mathrm{p}}}$) can bring a $\tau_{\overline{\mathrm{p}}}$ measurement in this range.

Figure 1: The Cavendish torsion balance.

1 Domain of Validity of Physical Laws

A fascinating aspect of the topics covered by the 1994 SLAC Summer Institute is the successful application of natural laws derived from table-top experiments to the largest scale of length L conceivable today, L = 10^{26} m. If the experiments are done by expert experimentalists, their results are valid no matter how old they are. Let me recall two experiments that, combined with the recent observation of the star velocities in galaxies, suggest the existence of DARK MATTER. The Galileo experiment on the free falling masses from the Pisa tower[2] and the Cavendish torsion balance (Fig. 1) that verify the Newton law $|F| = G\frac{m_1 m_2}{r_{1,2}^2}$ are two wonderful examples of everlasting experimental results. A more recent example is the measurement of neutrino species carried out at SLC and LEP.

The most sophisticated codes to study supernovae explosions require the existence of three ν species to boost the exploding wave. So our own existence can be related to the three ν families for which the solar system, and we ourselves, are products of this elaborated star explosion for which we can be called STAR CHILDREN or recycled people, depending on your personal feeling.

Figure 2: Experimental situation.

2 Antimatter Search in Space

The presence of antimatter ($\overline{\mathrm{p}}$, $\overline{\mathrm{He}}$, ...) in cosmic radiation is of great interest because a large $\overline{\mathrm{p}}$ component or even a small $\overline{\mathrm{He}}$ presence in cosmic rays would be an indication of acceleration processes in antigalaxies, and thus, of the same antigalaxies' existence.

The present status of the antimatter search, based on a very small sample of antiprotons, can be interpreted in terms of collision of the primary cosmic protons with the interstellar medium acting as a galactic target. The experimental situation is illustrated in Fig. 2 (Ref. 4). Two recent balloon flights, BESS 93 and CAPRICE 94 from Lynn Lake, Canada, are supposed to improve the present situation. Some preliminary data from BESS have been reported and seem to confirm the simplest production and containment model—the Leaky Box Model with modest improvement. The CAPRICE 94 data are still under analysis.

2.1 Galactic Antiproton and CPT

What has CPT got to do with antiproton flux in the cosmic rays? One of the most durable composite objects we know of in the Universe is the proton. Its expected lifetime is

$$\tau_{\mathrm{p}}\ (p \to e^{+}\ \pi^{0}\ )\ \geq\ 10^{32}\ \text{years}$$

if CPT holds

$$\tau_{\mathrm{p}} \;=\; \tau_{\overline{\mathrm{p}}}\;.$$

If CPT is violated at a Planck scale (L $\sim 10^{-33}$ cm) and if the violation is proportional to m_p/M_{Pl}(M_{Pl} Planck mass), it has been shown[2] that

$$A(\overline{\mathrm{p}}\ \rightarrow e^-\ \pi^0\ )\;=\;A(\mathrm{p}\rightarrow e^+\ \pi^0\ )\;+\;C(\frac{m_P}{M_{Pl}})$$

and

$$\tau_{\overline{\mathrm{p}}}\;\sim\;5\cdot 10^{-31}M^2(\mathrm{GeV})BR(\overline{\mathrm{p}}\ \rightarrow e^-\ \pi^0\ )$$

for C $\sim$ 1, and then $\tau_{\overline{\mathrm{p}}} = 10^7$–$10^8$ years.

Laboratory experiments[3] have given, until now, a lower limit of $\tau_{\overline{\mathrm{p}}}$ in the range of one year. In the *Review of Particle Properties*,[5] the largest lower bound on $\tau_{\overline{\mathrm{p}}}$ is taken from the $\overline{\mathrm{p}}$ flux in the cosmic rays, $N_{\overline{\mathrm{p}}}\ (E_{\overline{\mathrm{p}}}\ )$, and is of order 10^7 years.

2.2 Antiproton Lifetime from $\overline{\mathrm{p}}$ Flux in Cosmic Rays

Here at SLAC and at the Summer Institute, the language of particle physics is more familiar than the cosmic ray one, even if they are quite similar. So let me present the connection between $\tau_{\overline{\mathrm{p}}}$ and $N_{\overline{\mathrm{p}}}\ (E_{\overline{\mathrm{p}}}\ )$ using the analogy in Table 1 showing the laboratory quantities and the galactic ones.

Lab	Galaxy
Primary beam (p)	Cosmic ray proton flux $N_p(E) \propto E^{-2.7}$
Target	Interstellar medium
Trapped secondary $\overline{\mathrm{p}}$	Produced secondary
Storage particle lifetime	$\tau_{\bar{\mathrm{p}}}$

Table 1:

The experimental upper limit on primordial antimatter from the ratio $\overline{\mathrm{He}}/\mathrm{He} \leq 10^{-5}$ leads to the conclusion that the universe, at least in the vicinity of our galaxy, is dominated by baryonic matter.

Let us assume that antiprotons in our Galaxy are produced by the local cosmic radiation colliding with the interstellar medium. The mean free path of the proton in our galaxy is evaluated from the boron/carbon ratio and is between 5–10 g/cm^2 equivalent of hydrogen between injection and detection. The lower limit is more probable for high energy proton $E_{\overline{\mathrm{p}}} \geq 6$ GeV, required by the energy threshold E$_{th}$ for the reaction

$$\mathrm{p\,p} \longrightarrow \mathrm{p\,p\,\overline{p}\,p}. \tag{1}$$

The kinematics of Eq. 1 implies an antiproton energy spectrum $N_{\overline{\mathrm{p}}}\,(E_{\overline{\mathrm{p}}})$ starting from ∼0.3 GeV kinetic energy. The value of $dN_{\overline{\mathrm{p}}}/dE$ may be computed using the measured inclusive cross section $d\sigma_{\overline{\mathrm{p}}}/dE'$ of the process p p → $\overline{\mathrm{p}}$ X and is given by:[6]

$$\frac{dN_{\overline{\mathrm{p}}}}{dE} \sim 2\frac{<y>}{m_p}\int_E^\infty \frac{d\sigma_{\overline{P}}}{dE}(E,E')\frac{dN_0}{dE'}dE' \quad ,$$

where $<y>$ is the mean free path in g/cm^2, and for E $\gg$ E$_{th}$ the result is that

$$\frac{N(\overline{\mathrm{p}}\,)}{N(\mathrm{p})} \;\sim\; 5\times10^{-4}. \quad [\mathrm{Ref.\,6}]$$

The few events of $\overline{\mathrm{p}}$ collected until now are not in disagreement with this prediction. For an antiproton lifetime $\tau_{\overline{\mathrm{p}}} \gg \tau_{esc}$, the equilibrium equation for the antiproton flux is given by the equality between the $\overline{\mathrm{p}}$ sources and losses

$$\left(\frac{1}{\lambda_{\,esc}} + \frac{1}{\lambda_{\,\overline{\mathrm{N}}}}\right)\Phi_{\overline{\mathrm{p}}}\,(E_{\overline{\mathrm{p}}}\,) \;=\; \frac{q_{\overline{\mathrm{p}}}\,(E_{\overline{\mathrm{p}}}\,)}{4\pi\rho}. \tag{2}$$

If the possibility of the $\overline{\mathrm{p}}$ decay is introduced, Eq. 2 becomes

$$\left(\frac{1}{\lambda_{\,esc}} + \frac{1}{\lambda_{\,\overline{\mathrm{N}}}} + \frac{1}{\rho\beta c\tau_{\overline{\mathrm{p}}}\,\gamma}\right)\Phi_{\overline{\mathrm{p}}}\,(E_{\overline{\mathrm{p}}}\,) \;=\; \frac{q_{\overline{\mathrm{p}}}\,(E_{\overline{\mathrm{p}}}\,)}{4\pi\rho}$$

giving $\tau_{\overline{\mathrm{p}}} \geq 10^7$ years.

If both experimental data on the $\overline{\mathrm{p}}$ flux and theoretical prediction improve, the limit on $\tau_{\overline{\mathrm{p}}}$ can improve by an order of magnitude, becoming close to the value 10^8 years.

Recently, two new missions with stratospheric balloons have been launched, aiming to improve on the experimental data. One balloon detector built by a

Figure 3: BESS apparatus configuration.

Japanese-American collaboration is nicknamed BESS; the second one is prepared by the WIZARD Collaboration and named CAPRICE.

Preliminary results from a first analysis on BESS data report four antiprotons in the range 0.3–0.6 GeV and a $\overline{\mathrm{p}}/\mathrm{p}$ ratio $\sim 3.5 \cdot 10^{-5}$, not in disagreement with the simple model. A schematic view of the BESS detector is shown in Fig. 3. The CAPRICE flight from Lynn Lake on August 8 looks, from a preliminary analysis, capable of providing solid data, but unfortunately, the analysis on the $\overline{\mathrm{p}}$ has just started. So at the moment, the new experimental data do not allow an improvement on the lower limit of $\tau_{\overline{\mathrm{p}}}$: $\tau_{\overline{\mathrm{p}}} \geq 10^7$ years.

3 The WIZARD Facility

The WIZARD Collaboration has done many missions with different primary goals. Each mission has its own nickname. The latest mission from Lynn Lake (geomagnetic cutoff $\sim$ 0.3 GeV/c) is named CAPRICE (Fig. 4), and the main goal is measurement of $\overline{\mathrm{p}}$ flux in the range 1–10 GeV/c.

The general approach of the WIZARD mission is to use a balloon-borne magnet equipped with a tracking system and ancillary detectors. The tracking system allows measurement of the particle's magnetic rigidity (momentum/charge including the sign of the particle's charge in the range 0.5–50 GeV/c). In the CAPRICE

Figure 4: CAPRICE apparatus configuration.

flight, the ancillary detectors are a ring-imaging Cherenkov counter and a Si-W calorimeter with eight radiation lengths (X_0) of W (1 $X_0 = 3.5$ mm) in 1 X_0 steps.

The balloon flights have to respect some special conditions determined by the total weight and power requirement: weight $\leq$ 4000 kg, power $\leq$ 400 Watts. The mechanical configuration of the spectrometer as well as the single detectors must tolerate accelerations of $\sim$ 10 g.

To illustrate the capability of this detector, a typical high-energy spectrometer sent to the sky, I will present some preliminary data on the analysis of Flight TS93. TS93 flew for 26 hours in the skies over New Mexico starting from Fort Sumner (known to be the real grave of Billy the Kid) with a geomagnetic cutoff close to 5 GeV/c.

4 TS93 Preliminary Results

The TS93 instrument configuration is shown in Fig. 5. A superconducting magnet equipped with multiwire proportional chambers and drift chambers is used as a spectrometer.[7,8] A set of plastic scintillators, installed at the upper and lower extremes of the tracking system, provides both the trigger for the experiment and time of flight (TOF) information with a resolution of 400 ps over $\sim$ 1.4 m of the path; an energy loss (dE/dx) measurement over a thickness of 1+1 cm of the

Figure 5: TS93 apparatus configuration.

plastic scintillators is provided as well. The two other detectors used in the TS93 flight are a Transition Radiation Detector (TRD) and a silicon tungsten (Si-W) imaging calorimeter. The TRD consists of ten layers of carbon fiber radiators, each followed by a large area MWPC (an additional radiator was located at the top of the stack). The signals from each wire of each chamber were individually analyzed with a cluster-counting capability.[9–11] The calorimeter has five silicon planes, sensitive in both X and Y coordinates. The planes are interleaved with 1 X_0 of W. In order to determine the required performance of both the TRD and the calorimeter for particle identification, the signal/background ratio at balloon altitudes has to be taken into account. The expected positron to proton ratio is $e^+/\mathrm{p} \sim 10^{-4}$, and the positron to alpha ratio is $e^+/\alpha \sim 10^{-3}$ (in the energy range available for TS93). Therefore, the system TRD + Si-W calorimeter must have a greater than 10^5 separation power for protons and positrons. A drawing of the experimental detector, launched in Fort Sumner, New Mexico (The Land of Enchantment) on September 8, 1993, is shown in Fig. 5. A cosmic ray coming from outside the Earth will cross approximately 3.2 g/cm^2 of residual atmosphere and then, entering the payload, will find in this order the TRD, the top TOF counter, the tracking system, the bottom TOF counter, and finally, the Si-W imaging calorimeter.

Figure 6: Rigidity of noninteracting particles.

4.1 The Si-W Imaging Calorimeter

The sampling layer of the calorimeter is an array of an 8 × 8 pair (X-Y) of detectors (6 × 6 cm^2, divided in 16 strips, each 3.6 mm wide).[12] The strips in each coordinate are connected in parallel and the readout is performed through 16-channel preamplifiers. Each sampling layer consists of two arrays having $128 + 128$ readout channels.[13] A built-in system,[14] equipped with ADCs and digital processors, accomplishes the data acquisition and the reduction operations. The Si-W calorimeter performance has been measured with a prototype with better containment (9 X_0) but smaller lateral size at the CERN T7 test beam. A detailed description of the design concept and of test beam results are given in Ref. 12. The calibration of the detector has been done using noninteracting protons with energy > 5 GeV, which define our "mip" unit of energy loss.

4.2 Preliminary Results of Particle Identification

In Fig. 6, the rigidity distribution of particles as measured in the tracking system is shown; negative values apply to negative-charged particles which show a curvature in the spectrometer opposite to that of positive ones.

Figure 7: Truncated mean energy loss of noninteracting particles with rigidity greater than 4 GeV/c.

A plot of the average energy loss in the calorimeter for noninteracting particles obtained over five out of ten silicon planes with the truncated mean method is shown in Fig. 7. The dE/dx distribution clearly shows two peaks. The first peak is around 1 mip (protons) and the second at 4 mips (helium). Typical patterns of noninteracting and interacting helium nuclei (α particles) as seen in the calorimeter are shown in Figs. 8 and 9 together with the number of equivalent mips deposited in each silicon layer. The same truncated mean method, applied to the distribution of the α energy loss multiplied by a β^2 factor, gives the results shown in Fig. 10; the β value is computed from the rigidity measurement assuming the ^{4}He mass. A few events with Z = 3 have also been detected; the calorimeter reconstruction of one of these events is shown in Fig. 11. Their energy losses as seen in the first plane of the calorimeter and in the top plastic scintillator are shown in Fig. 12. The electron candidates are searched for among the negative particles with rigidity value less than –4 GeV/c. The electromagnetic shower development in the longitudinal and transverse directions has been studied using Monte Carlo calculations previously adapted to the test beam data (GEANT code[15]). The obtained algorithm has been optimized using the experimental data obtained from the test beam prototype. The application of this recognition technique allows us

Figure 8: Noninteracting α particle. Numerical values are in mip.

Figure 9: Interacting α particle. Numerical values are in mip.

Figure 10: Truncated mean multiplied by β^2 for α particles.

Figure 11: Reconstructed track in the calorimeter of one particle selected as lithium. Experimental data, rigidity greater than 4 GeV/c and less than 50 GeV/c. Numerical values are in mip.

Figure 12: Detected energy. (a) First plane of the calorimeter. (b) Top scintillators.

to select electron and positron events. Figure 13 shows an electron candidate with energy 4.8 GeV, Fig. 14 shows what has been identified as a positron candidate, and the TRD information is also shown; Figure 15 is an expanded view of an electromagnetic shower.

5 Dark Matter and Antimatter Searches in the Cosmic Flux

If the measured positron and antiproton fluxes are not reproduced by the secondary production hypothesis, it is very interesting to investigate the possibility of new sources. Recently, it has been suggested that the “excess” of e^+ and $\overline{\mathrm{p}}$ could be explained by annihilation of heavy supersymmetric particles that are at the same time good candidates for dark matter in the galaxies.[16]

Figure 13: Electron candidate in the TS93 apparatus.

Figure 14: Positron candidate in the TS93 apparatus.

Figure 15: Electromagnetic shower. Numerical values are in mip.

6 Conclusion

The recent and future space measurement of $\overline{\mathrm{p}}$ flux can improve on the lower limit on the $\overline{\mathrm{p}}$ lifetime $\tau_{\overline{\mathrm{p}}}$.

Searches for antimatter in the cosmic flux can give information on exotic sources if the antimatter in our galaxy is not all explained by production from the primary proton on the interstellar medium.

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